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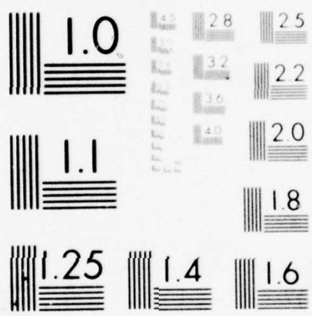

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Department of Physics and Astronomy
THE UNIVERSITY OF IOWA

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Observations of Ion Cyclotron Waves Within the Plasmasphere by Hawkeye-1*

by

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ABSTRACT

A survey of the plasma wave data from the Hawkeye-1 spacecraft has been performed in search of ion cyclotron waves associated with the scattering and loss of ring current ions within and near the plasmapause. During an 18 month period, consisting of about 270 orbits, a total of 5 events have been found with clearly detectable electric and magnetic fields at frequencies below the proton gyrofrequency. Comparisons of the electric and magnetic field amplitudes for these events provide~~s~~ strong evidence that these waves are ion cyclotron waves. All five events occurred during the recovery phase of a magnetic storm at radial distances within or very close to the plasmapause boundary. The results of this survey confirm and are consistent with the earlier identification of ion cyclotron waves by the Explorer 45 satellite. The Hawkeye-1 observations show that ion cyclotron waves of substantial amplitude occur at magnetic latitudes well away ($\sim 28°$) from the magnetic equator.

I. INTRODUCTION

During magnetic storms a ring current of energetic ions forms within the terrestrial magnetosphere. The ring current decays on a time scale varying from a few hours to several days. Two processes, charge exchange and pitch angle scattering by ion cyclotron waves, have been suggested to account for the decay. The charge exchange mechanism is a classical collision process involving the loss of hot ring current protons due to charge exchange with relatively cool neutral hydrogen atoms in the earth's exosphere. The charge exchange mechanism has been extensively investigated [Liemohn, 1961; Frank, 1967; Swisher and Frank, 1968; Smith et al., 1975] and is now regarded as a major, and possibly the dominant, loss mechanism for ring current protons. The pitch angle scattering mechanism involves the generation of ion cyclotron waves by the injected ring current protons and the subsequent pitch angle scattering and loss of these particles by resonant interactions with the ion cyclotron waves. Cornwall et al. [1970] first suggested that the ring current ion distributions could be unstable to the growth of ion cyclotron waves within the plasmasphere. From very general principles it can be shown that the wave growth is accompanied by a decrease in the pitch angle of the resonant particles, thereby causing diffusion toward the loss cone. For resonance to occur the ions must have a minimum energy parallel to the magnetic

field which is typically several keV. All ions with energies greater than this minimum energy resonate with ion cyclotron waves in the regions near the equatorial plane [Lyons and Thorne, 1972]. The ion cyclotron loss mechanism is consistent with Explorer 45 observations which show that pitch angle diffusion only occurs above a well defined minimum parallel energy during a magnetic storm [Williams and Lyons, 1974a, b].

In addition to ion cyclotron wave growth at the equator, ion cyclotron waves may be amplified at latitudes as high as 25° [Joselyn and Lyons, 1976]. These waves may then propagate toward the equator where they resonate with ions whose parallel energy and pitch angle anisotropy are insufficient for equatorial wave growth.

Magnetic fields attributable to ion-cyclotron waves have been observed by the Explorer 45 spacecraft [Taylor et al., 1975; Taylor and Lyons, 1976] near the magnetic equator. During the Explorer 45 lifetime a total of 18 events were identified which could be due to ion cyclotron waves. About half of these events occurred inside the plasmapause, all of which were associated with the presence of ring current ions. The remainder occurred at or outside the plasmapause and did not correlate with the presence of ring current particles although they did occur during magnetic storms. Although the waves detected by Explorer 45 occurred during magnetic storms the occurrence of these events (only 18 cases during approximately 100 passes through the storm time ring current) is too small to provide convincing evidence that ion cyclotron waves play a major role in the scattering and loss of ring current ions. Since the integrated

magnetic field sensitivity of the Explorer 45 wave detector is only about 0.4γ, which is only slightly less than the ~ 1γ amplitudes expected for the ion-cyclotron waves [Cornwall, 1970], it is possible that the low occurrence rates may be simply due to the inadequate instrumental sensitivity.

Because of the uncertainties concerning the role of ion-cyclotron waves in the loss of ring current particles we have examined the Hawkeye-1 plasma wave data in search of such events. Hawkeye-1 is in a highly elliptical orbit with a period of 49.9 hours and an apogee located over the north pole. In comparison with Explorer 45 Hawkeye-1 has a slightly more sensitive magnetic field detector, with an integrated noise level of 0.08γ, which should improve the chances of detecting the ion-cyclotron turbulence. Because of the apogee location over the north pole Hawkeye-1 usually passes through the magnetic equator between $L = 2$ and $L = 3$ and samples magnetic latitudes up to 35° within the plasmasphere. The survey to detect ion-cyclotron waves was conducted by examining 18 months of data for signals in the 1.78 Hz, 5.62 Hz, 17.8 Hz and 56.2 Hz magnetic channels when the spacecraft was within 45° of the magnetic equator. Events for which fewer than four data points were obtained above the instrument noise level or for which the signal appeared to extend above the local ion cyclotron frequency were eliminated. Five events survived these criteria and these events are the basis for the results presented in this report.

II. EXPERIMENTAL RESULTS

The Hawkeye 1 plasma wave experiment is designed to detect magnetic fields in 8 frequency channels from 1.78 Hz to 5.62 kHz and electric fields in 16 frequency channels from 1.78 Hz to 178 kHz. Wave magnetic fields are detected with a single search coil aligned parallel to the spacecraft spin axis. The spacecraft spin axis is oriented nearly parallel to the ecliptic plane. The noise levels of the magnetic field sensor are shown in Table 2 and compared with the noise levels of the Explorer 45 instrument [Taylor and Lyons, 1976]. The frequency integrated sensitivity of the Hawkeye-1 magnetic field sensor is about 0.08γ. Electric fields are detected with a single electric dipole antenna, 42.45 meters tip-to-tip, oriented perpendicular to the spacecraft spin axis. Because of the large length of the electric antenna the electric field sensitivity is inherently better than the magnetic field sensitivity for detecting electromagnetic waves (even considering the large index of refraction of ion cyclotron waves). Although the electric antenna is very sensitive the electric field measurements have not proven to be very useful for detecting ion cyclotron waves because of the presence of electrostatic waves which cannot be distinguished from electromagnetic waves without using the magnetic field data. For this reason the identification of ion cyclotron waves has been based entirely on the magnetic field measurements.

An ion cyclotron wave propagating parallel to the ambient magnetic field produces magnetic fields perpendicular to the ambient magnetic field at a frequency less than the ion cyclotron frequency. Because of the search coil alignment, nearly parallel to the ecliptic plane, the Hawkeye-1 magnetic field measurements are not always optimal for the detection of ion cyclotron waves, particularly at high magnetic latitudes away from the equatorial plane. The average sensitivity to an ion-cyclotron wave is about a factor of 2 larger than the integrated noise level of .08γ and the actual sensitivity on a given pass varies over a large range depending on the detailed trajectory.

For this study the survey covered the entire period June 1975 to November 1975. A summary of all the events found during this study is given in Table 2. After applying the selection criteria 5 events of magnetic waves or turbulence were obtained. They range in L-shell from 2.0 to 4.0 and occur as much as 28° in latitude from the magnetic equator. The distribution in local time is weighted towards local morning. The spatial distribution of the events summarized in Table 2 is consistent with the calculations of Joselyn and Lyons [1976]. They predict a maximum latitude for ion cyclotron wave amplification of about 25° and a spectral peak between .1 and .4 of f_{H^+}, where f_{H^+} is the proton gyrofrequency. The maximum latitude of a signal observed by Hawkeye-1 is 28° and when spectral peaks occur they appear in the range .1 to .4 f_{H^+}. Typical amplitudes range from about 0.1 to 1.0γ.

The relationship of the five events to the ring current was investigated by examining D_{st} and the results are presented in Figure 1.

The time of the Hawkeye-1 pass through the magnetosphere for each event is marked by an arrow. All events occur during periods of negative D_{st} and, with the possible exception of the October 16, 1974 event, all occur during the recovery phase of magnetic storms. This does not prove that the magnetic signal correlates with the presence of energetic ring current ions but it is consistent with that argument.

To resonate with energetic ring current ions, ion cyclotron waves must be propagating in the high density region within the plasmasphere. The plasmapause may be detected on Hawkeye-1 by examining the electric field channels for waves trapped above the local plasma frequency [Gurnett and Shaw, 1973] where the 31.1 kHz electric channel corresponds to an electron density of $10/cm^3$. All of these events occur at electron densities greater than $10/cm^3$ except for the period 1836-1840 UT on 18 September 1974. In this case a magnetic signal was detected at an electron density as low as $5/cm^3$ before 1840 UT. In all cases the magnetic signal extends into a region with densities greater than $10^2/cm^3$.

An example of one of the events detected is presented in Figure 2 for 8 July 1974. The spectrogram illustrates the output of the 8 magnetic channels with a range of 100 dB in each channel. Scales for time, magnetic latitude, L-shell and magnetic local time are provided to order the data. The onset of plasmaspheric hiss occurs at about 0305 UT in the 1.78 kHz and 5.62 kHz channels. This onset places the plasmapause at roughly L = 4 and this position is further confirmed by examination of the electric record for trapped radiation above the

plasma frequency. The magnetic signals believed to be ion cyclotron waves are present between 0319 UT and 0331 UT, primarily in the 5.62 Hz channel but occasionally in the 17.8 Hz channel as well. The proton cyclotron frequency, f_{H+}, is approximately 20 Hz during this period. Substantial fluctuations in the magnetic field intensities are evident as the spacecraft passes through the region where the $f < f_{H+}$ waves are detected, indicating that the waves consist of short transient bursts rather than a constant continuous level of turbulence.

Calibrated magnetic and electric spectrograms for three consecutive spectrums during the most intense signals of 8 July 1974 are shown in Figure 3. A definite peak in the magnetic spectrum exists at about 0.25 f_{H+}. Above f_{H+} the magnetic signal drops first to the noise level and then increases due to plasmaspheric hiss above 100 Hz. The electric spectrum closely resembles the magnetic spectrum by peaking in the 5.62 Hz channel then dropping to a low level at 56.2 Hz and responding to plasmaspheric hiss above 100 Hz. The similar behavior of the electric and magnetic spectrums and the spectral peak below the local ion cyclotron frequency are consistent with the detection of ion cyclotron waves.

A more sensitive test of the wave properties is to examine the spectral behavior of the index of refraction. For an ion cyclotron wave propagating parallel to the magnetic field the index refraction is given by $n = B/E$. The plasma wave receiver needs 20 seconds to record a spectrum and in most cases fluctuations in E and B are large over 20 seconds. However in one case, 8 July 1975, the electric and

magnetic signal was almost constant during several measurements of the spectrum. This allows the index of refraction to be determined and the result is presented in Figure 4.

The index of refraction for an electromagnetic wave propagating parallel to the magnetic field in a cold plasma is given by,

$$n^2 = 1 - \frac{\omega_{pi}^2}{\omega(\omega \pm \omega_{ci})} - \frac{\omega_{pe}^2}{\omega(\omega \mp \omega_{ce})} \qquad (1)$$

where the upper sign corresponds to the whistler mode (right hand polarization), the lower sign corresponds to the ion cyclotron mode (left hand polarization), and ω_{pi}, ω_{pe}, ω_{ci}, and ω_{ce} are the ion and electron plasma frequencies and the ion and electron cyclotron frequencies respectively. The index of refraction for the R and L modes is plotted as two dark lines in Figure 4. The magnetic field used in these calculations was determined by the on-board magnetometer while the electron density has been chosen to give the best fit. At low frequencies the index of refraction of the two modes are nearly equal corresponding to the two Alfvén modes. As the frequency of the ion-cyclotron (L) mode approaches the ion cyclotron frequency the index of refraction goes to infinity. For the electron cyclotron mode (R) the index of refraction decreases over this frequency range.

The index of refractions computed from the Hawkeye electric and magnetic spectral density measurements are presented as dots in Figure 4. No magnetic field was detected in the 1.78 Hz magnetic channel so that frequency is not shown. For the other frequencies the

measured B/E ratios are seen to be in good agreement with the index of refraction computed using equation (1). The possibility that the magnetic signals are caused by the spacecraft motion through spatial gradients in the ambient magnetic field is eliminated by these comparisons. The only frequency at which the left and right hand modes can be distinguished is 17.8 Hz, which is slightly below the proton gyrofrequency. At this frequency the B/E field ratios are about a factor of 1.2 to 3.0 times larger than the best fit index of refraction for the right hand polarized mode, suggesting that these waves are associated with the resonance at f_{H+} for the left hand mode. Although this analysis does not clearly distinguish between the two modes below the ion cyclotron frequency the increase in the index of refraction in the 17.8 Hz channel strongly suggests that left-hand polarized ion cyclotron waves are present in this frequency range.

The survey presented here is similar to one made from Explorer 45 [Taylor et al., 1975; Taylor and Lyons, 1976] which used a search coil with an integrated sensitivity of .4γ. The Hawkeye-1 search coil, after alignment considerations, probably has an average sensitivity about three times better than Explorer 45. The Explorer 45 orbit is in the equatorial plane which, although limiting its latitudinal coverage, permits thorough L-shell coverage where the growth rate of ion cyclotron waves is the largest. To compare the two surveys the event frequency per orbit was calculated for each spacecraft. If the magnetic signal events are short lived compared to the Explorer 45 orbital period of 8 hours and if Hawkeye-1 and Explorer 45 have nearly the same

chance of intersecting an event on a specific orbit, their event frequencies per orbit should be similar. Taylor and Lyons [1976] report 18 events in 17 months of data while Hawkeye-1 observes 5 events in 18 months of data. Taking into account the different orbit periods we estimate that Explorer 45 observes about 1.2×10^{-2} events/orbit while Hawkeye-1 observes about 1.8×10^{-2} events/orbit. These very similar event frequencies, although calculated from a small number of events, support the hypothesis that both Explorer 45 and Hawkeye-1 are detecting the same type of wave.

III. SUMMARY AND DISCUSSION

When substantial intensities of ring current ions are present within the plasmasphere ion cyclotron waves are expected to produce a continuous but weak background of electromagnetic turbulence at frequencies below the ion cyclotron frequency. The maximum broadband magnetic field amplitude of this turbulence is expected to be about 1γ [Cornwall et al., 1970]. In the appropriate frequency range for detecting these waves, from about 1.78 to 56.2 Hz, the broadband magnetic field sensitivity of the Hawkeye-1 plasma wave experiment is about 0.08γ. Because of the unfavorable alignment of the antenna axis the average threshold sensitivity is probably a factor of 2 higher for detecting parallel propagating ion cyclotron waves at the equator. This threshold sensitivity is slightly better, by about a factor of 3, than the previous Explorer 45 measurements.

The survey to detect ion-cyclotron waves was conducted by searching for signals in the 1.78 Hz to 56.2 Hz magnetic field channels when the spacecraft was within 45° of the magnetic equator. During an 18 month period, consisting of about 270 orbits, a total of 5 events were found which were consistent with the properties of ion cyclotron waves. All of these events occurred during periods of negative D_{st} and, with the possible exception of one event, during recovery phases of magnetic storms. Although these events were associated

with magnetic storms, and presumably the ring current particles, several passes (14 cases) were also found in which no ion-cyclotrons were observed even though there was a substantial depression in D_{st} ($> 25\gamma$) at the time of the pass through the magnetosphere. The maximum magnetic field values for the 5 events detected were occasionally quite large (1γ) and the magnetic fields frequently exhibit large spatial gradients. The ion cyclotron waves proposed by Cornwall et al. [1970] to account for the essentially continuous loss of ring current ions during a magnetic storm is an essentially continuous background of waves. With the exception of the event on July 8, 1975, the magnetic signals observed by Hawkeye-1 do not represent a smooth continuous background.

For the 5 events detected by Hawkeye-1 electric field signals were also detected with spectrums similar to the magnetic field spectrum, as expected for the electromagnetic ion cyclotron mode. In one case the magnetic and electric field spectrums were sufficiently constant in time to determine the index of refraction from the magnetic to electric field ratio. The computed magnetic to electric field ratio at frequencies below the proton cyclotron frequency show an increase consistent with the resonance in the index of refraction expected for the ion cyclotron mode at the proton cyclotron frequency. Although the polarization cannot be measured, these comparisons provide convincing evidence that the waves detected below the proton gyrofrequency are ion cyclotron waves.

In general we feel that the results of this study are in close agreement and confirm the earlier studies of Taylor et al. [1975] and Taylor and Lyons [1976] using the Explorer 45 spacecraft. Although the Hawkeye-1 magnetic field measurements are somewhat more sensitive than the Explorer 45 measurements the quantitative characteristics of the ion-cyclotron waves detected are essentially the same. Both spacecraft occasionally detect ion-cyclotron waves in association with magnetic storms but neither spacecraft detect these waves sufficiently often to conclusively prove that ion-cyclotron waves play a dominant role in the loss of ring current ions.

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Table 1

Hawkeye-1		Explorer 45	
Center Frequency, Hz	Noise Level γ^2 Hz^{-1}	Center Frequency, Hz	Noise Level γ^2 Hz^{-1}
1.78	4.7×10^{-3}	1.7	4.9×10^{-3}
5.62	1.5×10^{-5}	5.5	4.0×10^{-4}
17.8	3.2×10^{-7}	17.	1.0×10^{-5}
56.2	1.6×10^{-8}	55.	1.3×10^{-7}
178.	4.2×10^{-9}	170.	8.8×10^{-9}

Table 2

Event Date and Time (UT)		MLT (hr)	MLAT (deg)	L-Shell	Maximum Magnetic Field Amplitude (γ)
1974 July 8 (189)	0319-0331	12.8	9.0 → 1.8	3.4 → 2.7	0.81
1974 September 16 (259)	1540-1552	8.1	12.5 → 8.5	2.7 → 2.5	0.20
		8.3	3 → -1	2.2 → 2.0	0.20
1974 September 18 (261)	1836-1901	8.0	20 → -10	4.0 → 2.1	0.10
1974 October 16 (289)	1332-1341	6.4	8 → -2	2.4 → 2.0	0.94
1974 July 8 (189)	1233-1245	.1	-28 → -15	3.2 → 3.2	0.09

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FIGURE CAPTIONS

Figure 1 D_{st} values for periods including the 5 magnetic wave or turbulence events seen by Hawkeye 1. The arrows correspond to the time of each event.

Figure 2 Output of the 8 magnetic channels of the plasmawave receiver during the 8 July 1974 magnetic event. Full scale is 100 dB of power. The proton cyclotron frequency at 0330 UT is about 21 Hz.

Figure 3 Magnetic and electric spectral densities during the peak signal of 8 July 1974. The three spectrums, in each case, are measured consecutively over a period of one minute.

Figure 4 The spectral behavior of the index of refraction for the 8 July 1975 magnetic event. The dots are magnetic to electric field ratios from Hawkeye while the solid lines are the index of refraction for the right and left handed polarized modes for propagating parallel to a magnetic field in a cold plasma. The increased B/E ratio in the 17.8 Hz channel, near the resonance at f_{H+}, suggests that the waves detected in this frequency range are left hand polarized ion cyclotron waves.

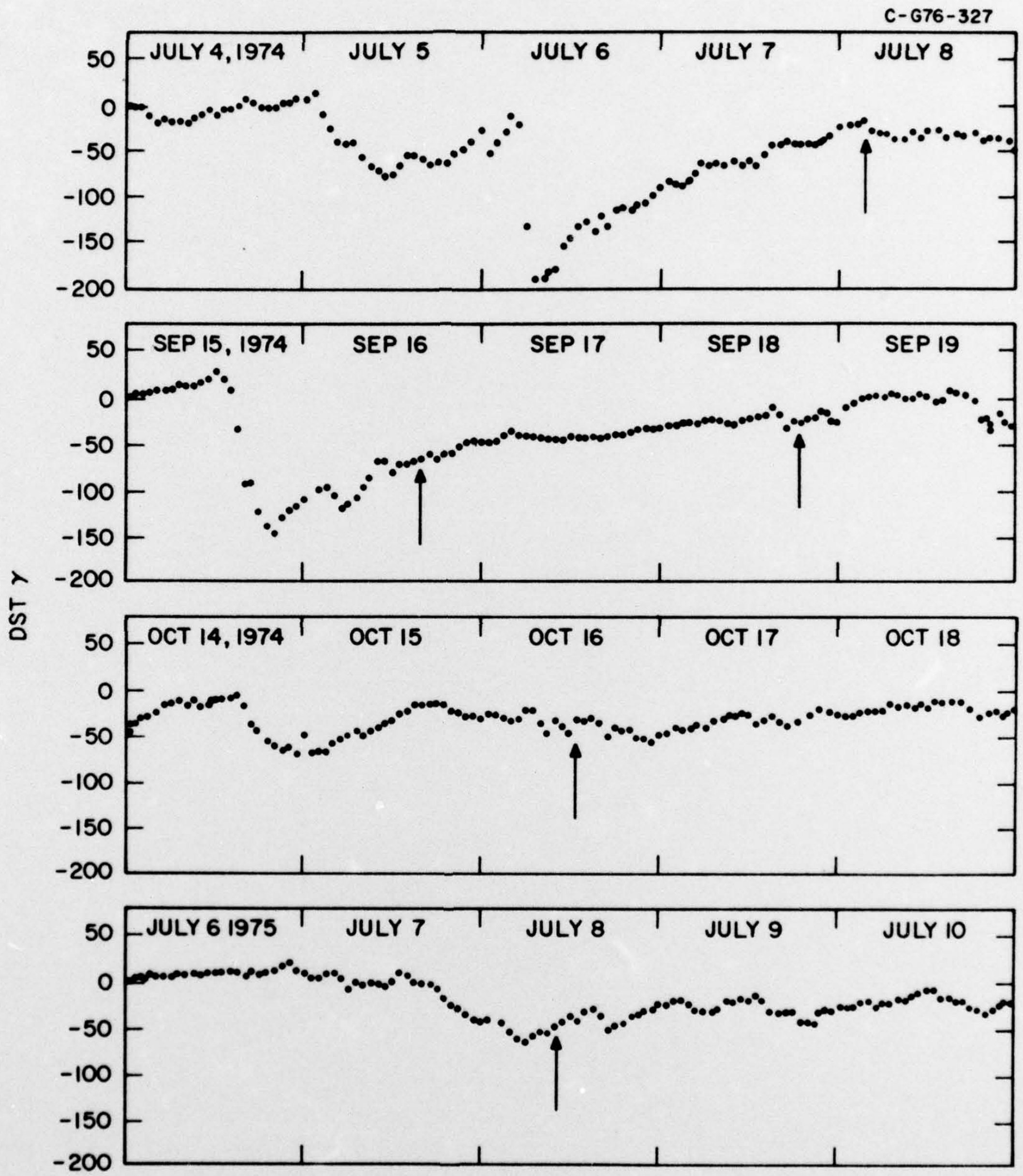
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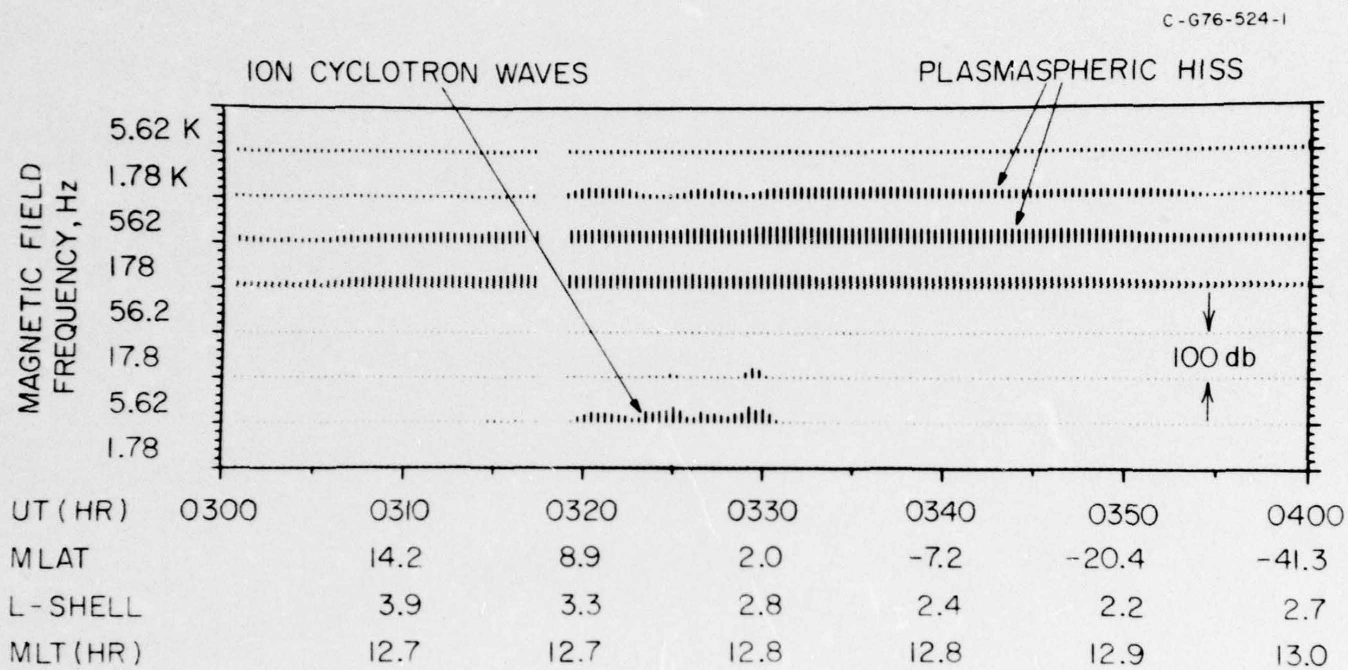
Figure 1



HAWKEYE 1, 8 JULY 1974

Figure 2

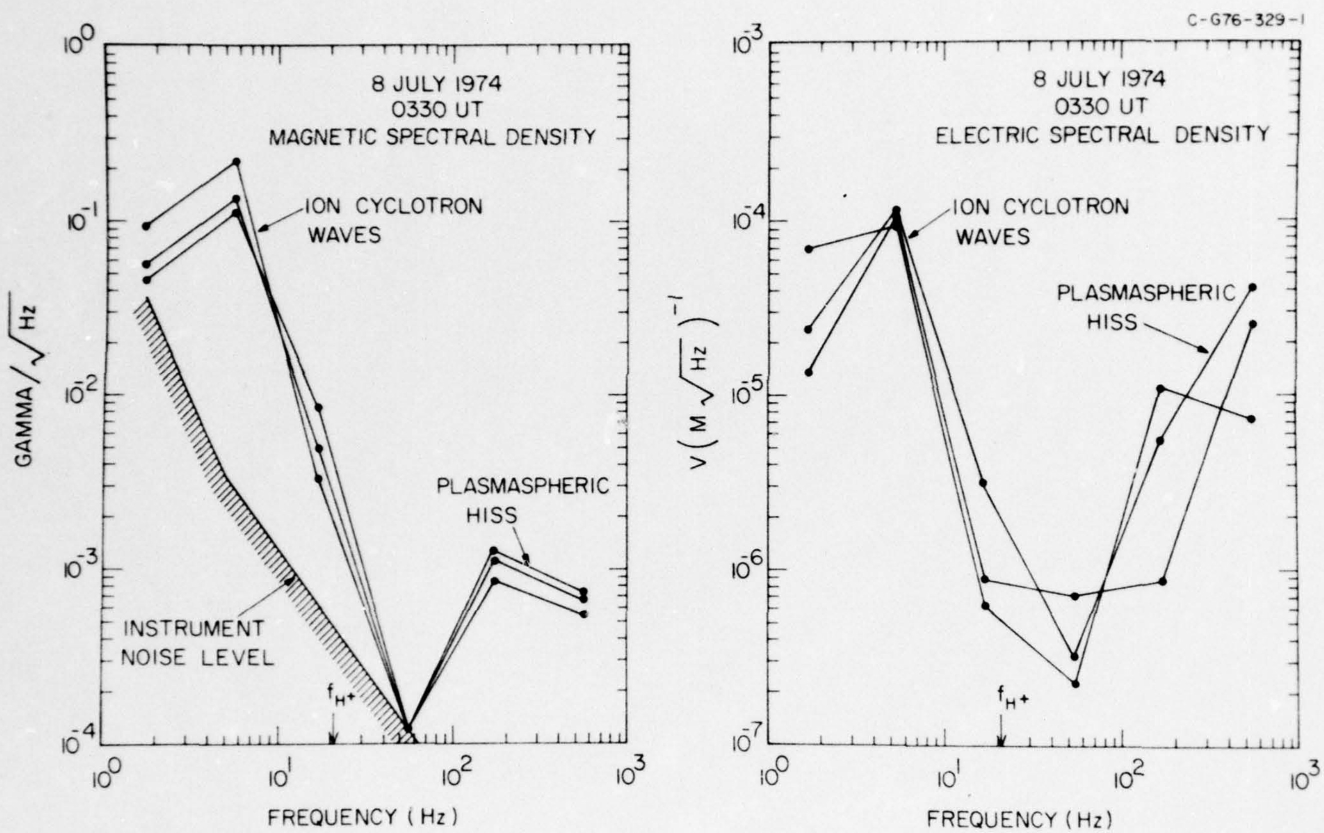

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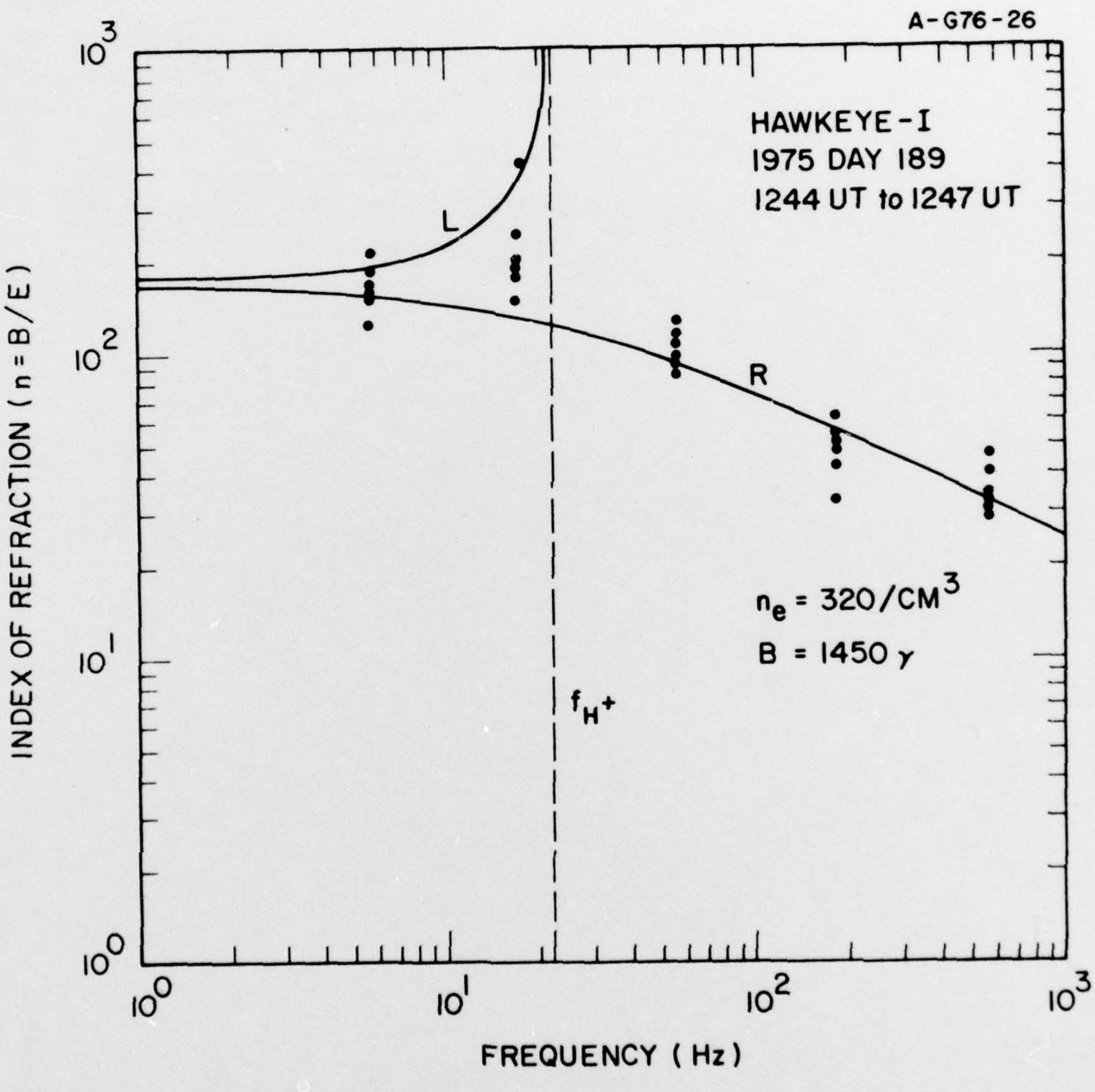
Figure 3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10^2
10^3

Figure 4